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WT4 Millimeter Waveguide System:

Mechanical Gauging Techniques

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For the WT4 waveguide system, mechanical measurements of the sheath, tubing, and waveguide were necessary before and after installation to ensure conformity to the manufacturing specifications, to verify the quality of installation techniques, and to acquire a better theoretical understanding of the effects of geometric imperfections on electrical loss. To fulfill these requirements a family of mechanical gauges or "mice" was developed. These include mice to measure individual lengths of sheath, tubing, and waveguide both in factory and laboratory environments and mice to measure long lengths of installed waveguide. The principles of mice are discussed in general and two particular mice are described in detail.

I. INTRODUCTION

During the development of the WT4 waveguide system, mechanical measurements of the various geometric distortions in the waveguide were used extensively

To monitor the manufacturing processes to ensure conformity to the specification.

To correlate mechanical distortions in the waveguide and the field evaluation test line with electrical loss measurements to improve manufacturing processes and installation techniques.

To acquire a better theoretical understanding of the relationship between mechanical distortions and electrical loss.

In many cases mechanical measurements are of greater value than direct electrical measurements. The problems associated with making accurate electrical measurements on long waveguide runs at millimeter wave frequencies are well known[1]; those of attempting to measure di-

rectly the mode conversion loss in a single section of steel waveguide tubing are better imagined! In fact, even if such measurements could be made, they would still be of limited utility in that they usually could not identify the cause of loss but only indicate its presence. To see this problem in the proper perspective it should be remembered that in the WT4 waveguide system a serious distortion[2] which results in losses of 0.1 dB/km corresponds to a single tube loss of 0.001 dB. Consequently measurements of most of the individual loss components on a single tube require accuracies on the order of 10^{-5} dB. Electrical measurements of this accuracy are currently impossible in the 40 to 110 GHz band. By comparison the mechanical measurements required to characterize such distortions are relatively undemanding.

To facilitate these mechanical measurements a family of gauges, popularly known as "mice", was developed. The members of this family are

(*i*) An external sheath mouse used to measure the curvature of individual lengths of sheath in the factory.

(*ii*) An internal sheath mouse used to measure installed sections of sheath up to 1.6 km in length prior to the installation of the waveguide.

(*iii*) A tubing mouse used to measure diameter and curvature of individual lengths of steel tubing at the factory.

(*iv*) A rotating-head mouse which is used to completely characterize individual tubes in a laboratory and also in quality control applications.

(*v*) A long-distance mouse used to measure the complete field evaluation test line.

This paper discusses the principles of the gauges and describes the last two in detail.

II. PRINCIPLES OF MECHANICAL MEASUREMENTS

In millimeter waveguide systems a significant fraction of the total loss is a result of power being coupled out of the signal mode into various spurious modes by geometric imperfections. To characterize these losses the departures from the nominal geometry of the guide are usually expressed in the form originated by Morgan,[3] where the radial distortion, δr, measured at an angle θ from a reference plane at some position, z, along the guide is given by

$$\delta r(z, \theta) = \tfrac{1}{2}a_0(z) + \sum_{n=1} a_n(z) \cos n\theta + b_n(z) \sin n\theta \tag{1}$$

The Fourier coefficients $a_n(z)$ and $b_n(z)$ are then used to characterize the properties of the guide using techniques described in Rowe and

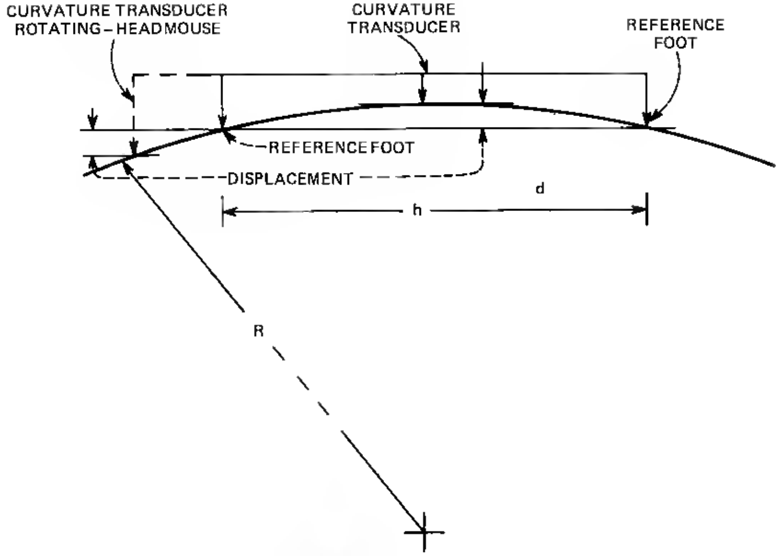

Fig. 1—Principle of measurement with three-point gauge.

Warters.[4] In this expression the a_0 coefficient represents the average radius, the a_1 and b_1 terms represent the offset of the guide axis from a straight line, and so on. Generally the summation index, n, is known as the *foil* and the associated distortion as $n - foil$. For describing the effects of offsets in the guide axis, it has been found that the *curvature* of the guide axis is a much more useful quantity than the offset itself. The primary reason for this choice is that curvature is insensitive to the exact position and orientation of the guide. For the simple gauge shown in Fig. 1 it can be seen that displacement of the movable probe with respect to the two fixed reference feet is a measure of the waveguide curvature or inverse bend radius and is equivalent to a second difference. If we assume for the moment that all distortions except the axis offset are negligible, the output of a mouse is the difference between a linear interpolation between its feet and the actual displacement of the probe. Denoting the distance between the fixed reference feet by h and the distance between the rear† reference foot and the probe by ph it is clear that the gauge curvature output in one plane is

$$x(z) = d(z) - p'd(z - ph) - pd(z + p'h) \tag{2}$$

where $p' = 1 - p$ and d is the axis displacement in that plane. It has been convenient to define the position of the gauge as that of its probe.

† We assume that the mouse is traveling in the positive z direction.

If such a mouse is used to measure a circular arc of radius R the output is approximately

$$x = \frac{h^2 pp'}{2R} \tag{3}$$

so that the sensitivity is proportional to h^2.

An alternative view of eq. (2) is to regard the mouse output as the result of a linear filtering operation on the displacement function and, if ω represents radian *mechanical* frequency, the transfer function of this filter is simply

$$H(\omega) = 1 - p' e^{i\omega ph} - p e^{-i\omega p' h} \tag{4}$$

The characteristics of the gauge when $p = ½$ are interesting, as this case corresponds to a classical symmetric second difference. In this case the transfer function reduces to $1 - \cos \omega h/2$ which has zeros at integer multiples of $2/h$. Since we are interested in curvature and not the direct gauge output, it is necessary to invert this transfer function. Consequently, the presence of zeros occurring in the frequency range of interest is undesirahle. One possihle solution is to make the length, h, of the gauge very short, hut the associated loss of sensitivity makes this solution impractical. On the other hand, the only penalty to the alternative solution of making the gauge nonsymmetric is that direct interpretation of the gauge output is slightly more complicated. If one examines the position of zeros in the response function, it is found that a zero can only occur at frequencies where hoth ph and $p'h$ are integer multiples of the wavelength. One choice which has heen used extensively is $p = 0.419$ which retains excellent sensitivity and also has no zeros out to 2000 cycles per meter. The power transfer function, $\omega^4/|H(\omega)|^2$, is shown in Fig. 2. The fact that this transfer function has a well-defined limit at $\omega = 0$ is a further consideration in favor of using curvature rather than offset.

III. THE ROTATING-HEAD MOUSE

The ahility of the three-point gauges described above to recover curvature information was conditioned on the magnitudes of the other distortions in the guide heing "small." If these distortions are not small the curvature gauge, while responding to them, cannot distinguish the nature of the distortion. To measure these coefficients unamhiguously the *rotating-head mouse* was developed. This gauge operates primarily in a lahoratory environment and, heing intended to completely characterize the geometry of the guide, has heen designed for exceptionally high angular resolution and sampling density.

The rotating-head mouse is shown in Fig. 3, in which its principal external features may he seen. There are two major sections, the "body,"

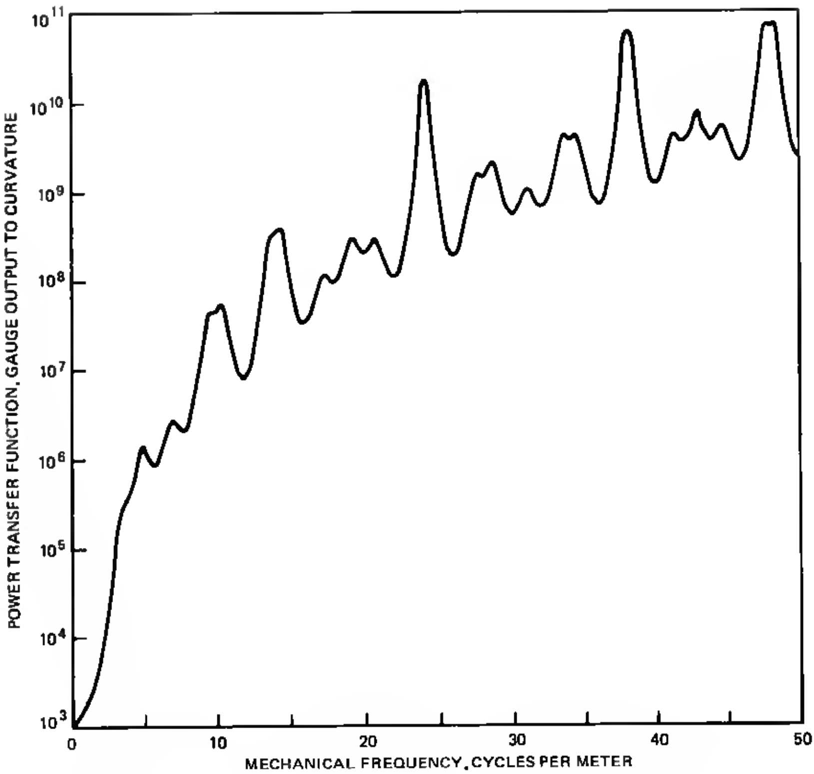

Fig. 2—Power transfer function for a three-point curvature gauge. Length $h = 0.5$ meter, offset $p = 0.419$.

and the "head." The body, like those of the curvature gauges described above, is supported by two pairs of carbide reference feet. These are positioned at ±45 deg from the vertical with one set at the rear of the gauge and the other close to the front. The head of the mouse contains a linear differential transformer and is supported by a precision needle bearing. The head is rotated by a small dc motor contained in the opposite end of the gauge housing. Signals from the differential transformer are brought out through slip rings and the angular orientation of the head is sensed by an optical encoder. Since the head is forward of both pairs of feet the parameter p is greater than 1 for this mouse, but the other considerations on its choice are identical.

The section of waveguide or tubing to be measured rests on two adjustable supports in line with a "measurements bench" and the mouse is moved through the tube by a push rod supported by the bench as suggested by the simplified block diagram, Fig. 4. The measurement and calibration procedures are controlled by a minicomputer. The mea-

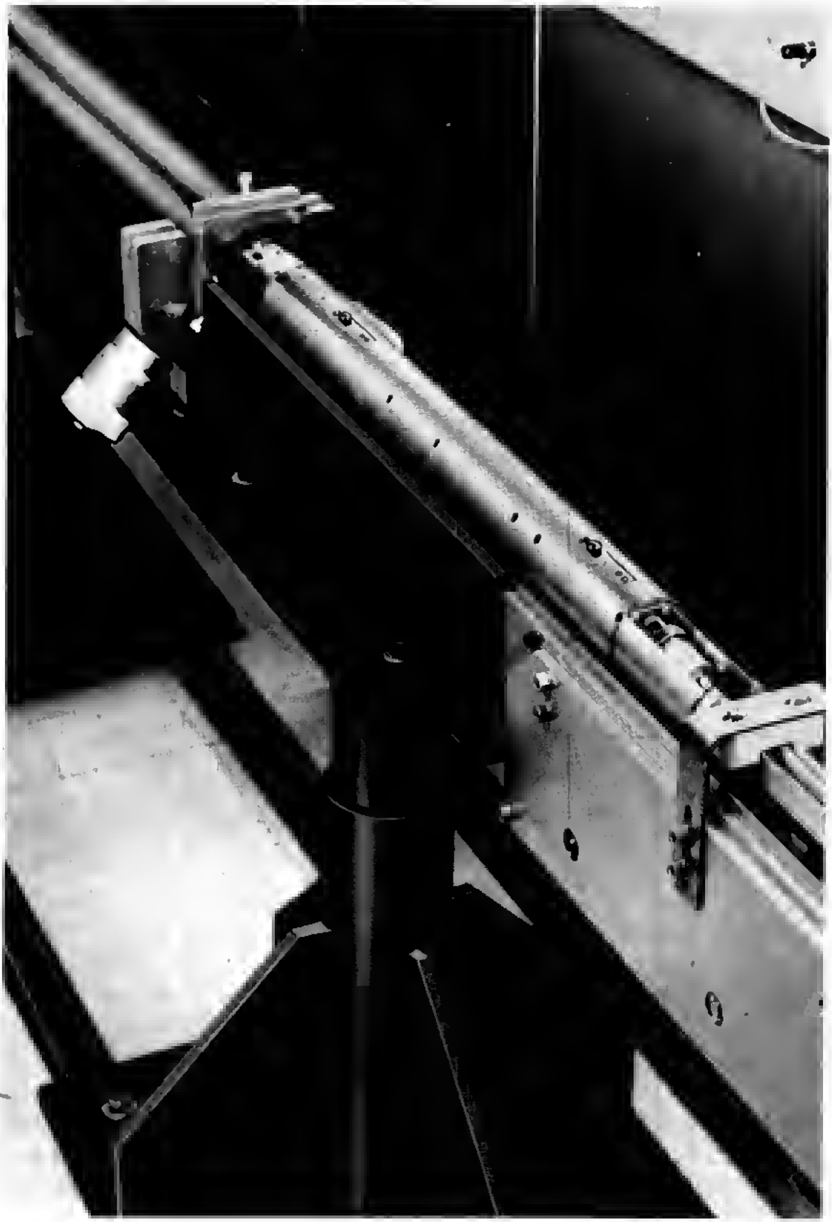

Fig. 3—Rotating-head mouse.

surement sequence which has been found most satisfactory is as follows:

(*i*) The section of tubing to be measured is supported at the "Airy"

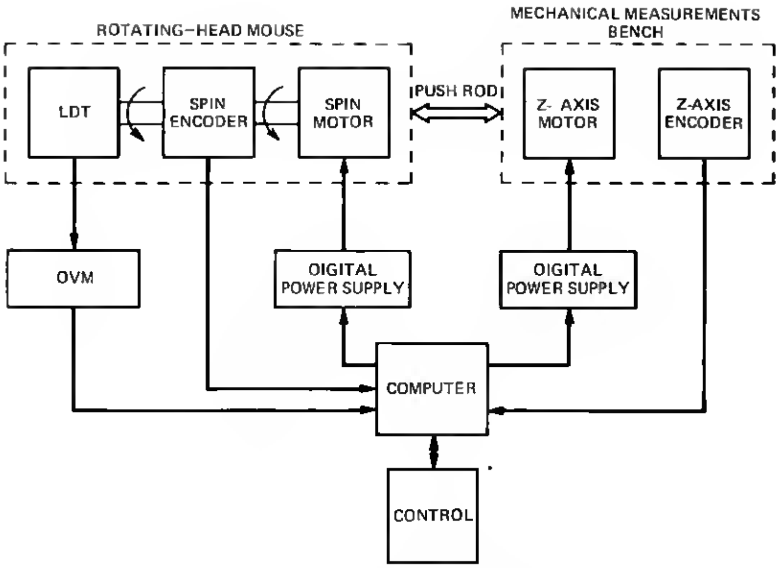

Fig. 4—Rotating-head mouse system block diagram.

points[5] so that there is zero curvature at the ends of the tube due to gravitational effects, and the gauge is positioned at the desired axial position.

(*ii*) The head is rotated for one revolution clockwise at a uniform speed. During this revolution measurements of the radial displacement are made at equally spaced angular increments (given by the optical encoder) using an integrating digital voltmeter.

(*iii*) The measurement is repeated at the same axial position with the head rotating counterclockwise.

(*iv*) The two sets of measurements are compared: if the agreement is good the average is recorded, but if either the mean square or maximum differences are larger than their respective limits, both measurements are repeated. The limit on the rms discrepancies between the two readings is typically less than 1 micron.

(*v*) The axial position is incremented and the process repeated.

The angular resolution and sampling requirements are determined primarily by the highest-order propagating mode and similarly the axial sampling interval is determined by the differential propagation constant or $\Delta\beta$ of this mode. For the electrical frequency range used in the WT4 system, 64 angular measurements per scan and a scan spacing of 2.5 mm have been commonly used. The accuracy requirements of this gauge are complex and, like the waveguides they measure, are specified in terms of the spectral density functions of the various Fourier coefficients. As

an example, the specification limit for the a_0 coefficient near *mechanical* frequencies of 1.3 cycles per meter is 6.5×10^{-2} microns^2/cycles/meter. The corresponding spectrum of steel tuhing at this point is approximately 3×10^{-3} μ^2/c/m and the equivalent noise level of the gauge about 2×10^{-4} μ^2/c/m. (The equivalent noise level is obtained by measuring a precision ring gauge *without* changing the axial position and normalizing the spectral density estimates of the coefficients by the axial step size used in the actual measurements. The observed noise results primarily from imperfections in the hearing and differential transformer.)

As is the case with most conceptually simple measurements, the actual theory and implementation of the rotating-head mouse are quite complex. In part this complexity results from the fact that the gauge cannot he huilt to arbitrary precision. The primary reason, however, for the overall complexity of the system is that it is used for measurement and not for synthesis and, prior to the measurement, the origin of the desired coordinate system is unknown. The result is that the radial displacement measurements are made from the center of the gauge head rather than from the center of the guide. We define the center of the guide to be that point about which the radial expansion coefficients a_1 and b_1 are both zero when the measurement plane is perpendicular to the mean axis of the guide. The guide axis is the locus of the center of the guide.

Temporarily suppressing the z coordinate we assume that a set of measurements $a(\phi)$ have been taken as a function of the angle ϕ measured with respect to the center of head coordinates. We further assume that the head is located at a point (τ, ω) from the center of the guide. The expansion in terms of the coordinates (r, θ) about the center of the guide, is by definition

$$\alpha_n + i\beta_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} r(\theta) e^{in\theta} d\theta \tag{5}$$

The two coordinate systems are related hy the elementary identities. To simplify notation rotate both θ and ϕ by $-\omega$

$$a^2(\phi) = r^2(\theta) + \tau^2 - r(\theta)\tau \cos\theta \tag{6a}$$

$$a(\phi) \sin\phi = r(\theta) \sin\theta \tag{6b}$$

$$a(\phi) \cos\phi = r(\theta) \cos\theta - \tau \tag{6c}$$

These can be substituted into eq. (1) by straightforward but tedious algebra and, because the distortions tolerable in millimeter waveguide systems are small, the gauge head is always close to the guide center and a series expansion of the correction in terms of the offset, τ, can be made.

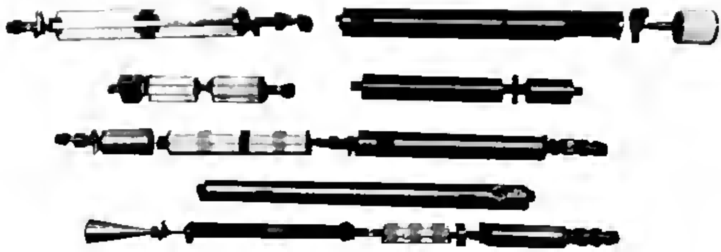

Fig. 5—Long-distance mouse.

The previous paragraph described the conversions between center of head and center of guide coordinate systems in the plane of the gauge head. To obtain meaningful curvature output from the gauge further corrections are necessary. The simplest of these corrections is a result of the gauge measuring a form of second difference of the guide axis displacement rather than an actual derivative and was discussed earlier. The present section is concerned with the influence of foils other than 1 on the apparent curvature.

Clearly the position of the gauge head depends on three distinct elements: the curvature of the guide axis and the positions of the two pairs of gauge feet. The positions of the feet depend on the distortions of the wall in the planes where the feet are located. In an idealized gauge the feet may be represented as vectors of length f_0 at angles of ±45 degrees from vertical. Since both of these contact the guide wall they define the position of the center of the gauge body in the plane of the feet. Simple but tedious trigonometric equations then give the position of the center of the gauge body relative to the center of the guide in the plane where the feet are located. Extrapolating these differences from both the forward and the back pairs of feet to the plane of the head gives a correction for the influeneces of foils other than 1 on the indicated curvature.

IV. LONG-DISTANCE MOUSE

The long-distance mouse, shown in Fig. 5, is a battery-powered self-propelled gauge especially designed to measure the curvature and diameter of long lengths of installed waveguide. The mechanical data, along with certain status information, are digitally encoded and transmitted through the waveguide itself to a base station, which also controls the mouse. Most of the runs in the field test installation were made with a reflecting piston attached to the tractor so that mode conversion losses as a function of distance could be obtained[1] at the same time as diameter

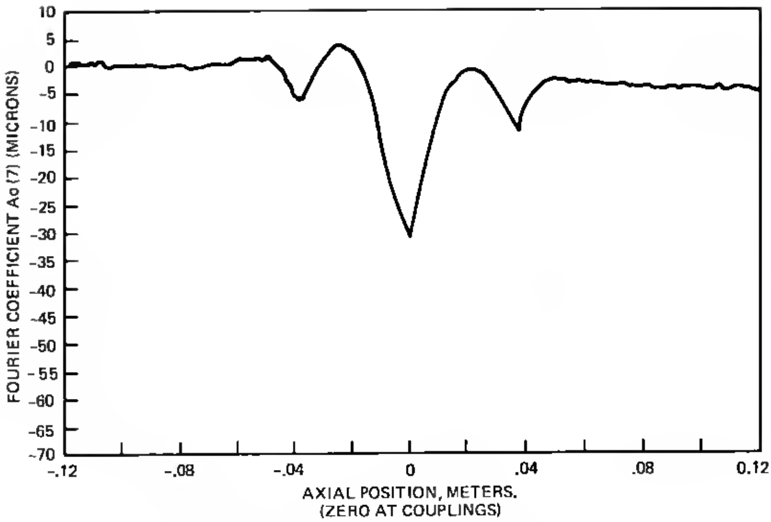

Fig. 6—Radius distortions in a welded coupling.

and curvature information. The data collected by the long-distance mouse contains information on both the placing and couplings, which cannot be present in measurements of individual tubes. Of these the distortions induced by welding the couplings, Fig. 6, contain the most detail, and to characterize this distortion a 1 cm sampling rate has been used for this gauge. While this sampling interval is much finer than required to characterize the placing operation, it provides sufficient redundancy to allow correction of occasional errors and to insure that unexpected high-frequency distortions that may be introduced by the installation procedure are detected.

The design represents a compromise between sensitivity, accuracy, and the necessities of fitting the equipment physically inside the waveguide. If the gauge is too short, eq. (3) implies that very high resolution is required, while if it is too long, one runs the risk of its becoming "stuck" in tight turns. An active length of 50 cm was chosen, representing a compromise allowing peak deflections of about ±1 mm, corresponding to a radius of curvature of about 27 meters and quantization errors of about 1 micron.

As was the case with the rotating-head mouse, the accuracy requirements of the long-distance mouse are complex. Figure 7 shows a set of measurements by the long-distance mouse of a coupling 2.2 km from one end of the field test. The data shown in the top frame, the vertical curvature output, are typical of a "tilt," or angular misalignment, at a coupling, while the data in the third frame, the horizontal curvature output, are typical of axial offset between the two guides. The second

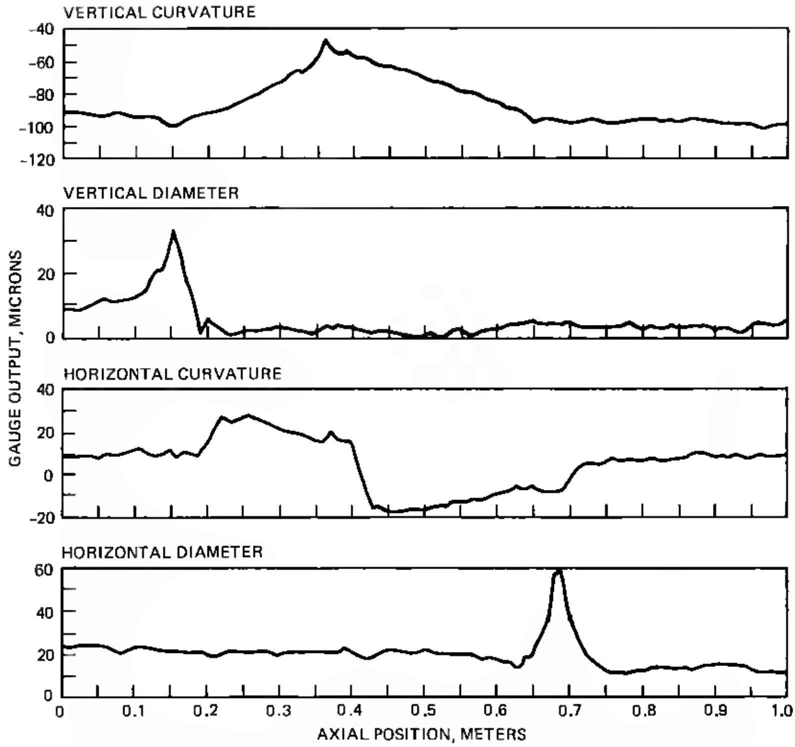

Fig. 7—Comparison of two long-range mouse measurements through a coupling. The apparent shift in location is a result of the transducer (see Fig. 10).

fourth frames represent the two diameter outputs. The long-term accuracy of the gauge is about 5 microns, while the short-term accuracy is much better, and details are reproduced with surprising accuracy. In these plots much of the low-amplitude "noise" is a result of the long-distance mouse running on wheels. Since the wheel noise is periodic at a known frequency, it is accounted for in the Fourier data analysis and, therefore, is of even less importance than it appears here.

As shown in the block diagram, Fig. 8, the long-distance mouse system consists of the following main components:

(*i*) Tractor
(*ii*) Stabilizer and torque isolator
(*iii*) Diameter and curvature gauge
(*iv*) Data encoder and command circuits
(*v*) Transmitter-receiver
(*vi*) Base station

These components will now be described in the above order.

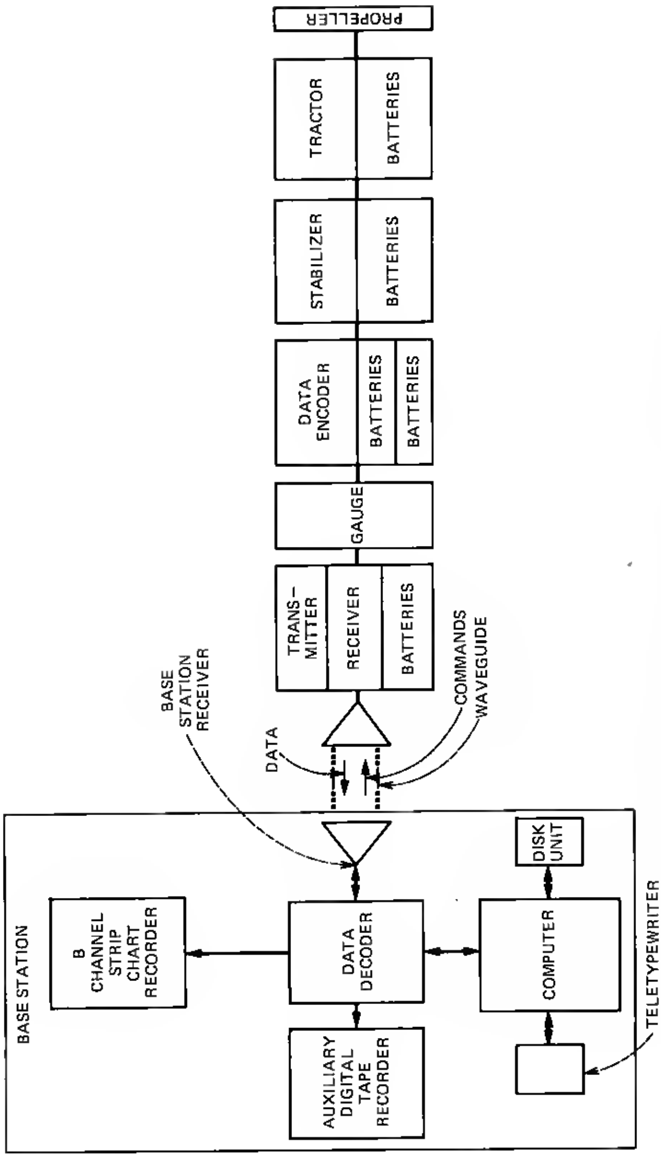

Fig. 8—Block diagram of field evaluation test mouse system.

Fig. 9—Detail of propeller and pneumatic piston.

4.1 Tractor

The tractor comprises a tubular body provided with eight wheels and containing a dc motor and control circuitry. External to the body is a "propeller" driven by the motor and a pneumatic piston, as shown in Fig. 9. The propeller consists of four pairs of rubber-tired wheels set at an angle of 20 deg with respect to the axis of rotation of the propeller and bearing against the inner wall of the waveguide. As the propeller rotates, it pulls the tractor and its train through the waveguide. Counterrotation of the tractor is opposed by four rubber-tired wheels located at 90 deg around the forward end of the body. These wheels, and the propeller wheels, are spring-loaded against the inner wall of the waveguide to provide a constant adjustable frictional force essentially independent of variations in the inner diameter of the waveguide (such as those encountered when going from the dielectric-lined guide to the helix mode filters).

Power for the motor is supplied by two 12-volt nickel-cadmium battery packs each having a capacity of 3 ampere-hours. To reduce battery drain a nitrogen "boost" is applied to the mouse in the direction of travel, the force being developed essentially across the restriction provided by the pneumatic piston. Maximum range with a boost of 0.14 kg/cm^2 (2 psi) is about 10 kilometers at the nominal velocity of 30 cm/sec. For runs of less than 5 km only one battery pack is needed.

4.2 Stabilizer and torque isolator

Angular orientation of the mouse is maintained to within ±0.5 deg by a servo stabilizer. An electrolytic potentiometer, whose resistance varies

Fig. 10—Diameter and curvature gauge.

with tilt, is connected to form two arms of a phase-sensitive bridge. A rubber-tired spider, bearing against the inner wall of the waveguide, is attached to the shaft of a servo motor and, as the shaft turns in response to the error signal, the mouse assembly rotates as a unit to null the signal, thereby maintaining orientation. Since the torque restraining wheels on the tractor have a residual angular slippage, the tractor rotates at a low rate in a sense opposite to the rotation of the propeller. To avoid wasting battery power in correcting this rotation, a torque isolator is interposed between the tractor and the stabilizer to isolate rotationally the tractor from the rest of the assembly. Signals to the tractor are coupled through slip rings.

4.3 Diameter and curvature gauge

The diameter and curvature gauge, shown in Fig. 10, has four transducers so that the diameter and curvature can be measured simultaneously in both the vertical and horizontal planes. For diameter measurements a transducer is placed opposite a curvature reference foot. The level sensor for the stabilizer is mounted on one end of the body and a second sensor, having a greater range (±11 deg as compared to ±1.5 deg for the former), is mounted on the other end to provide information for telemetry regarding the orientation of the gauge and to indicate any malfunction of the stabilizer.

4.4 Data encoder

Eight analog channels are sampled sequentially every centimeter of gauge travel: the outputs of the four transducers, the gauge angle, the

ground reference, the drive motor supply voltage, and the 5-volt supply. These analog voltages are digitized and ordered into 16-bit bursts by the data encoder. The first bit of each bit is always a logical "one" for synchronization, the next three bits are the octal channel number, and the last 12 bits are the encoded data. The timing sequence for a complete data transmission is shown in Fig. 11. Also included are controls for gain

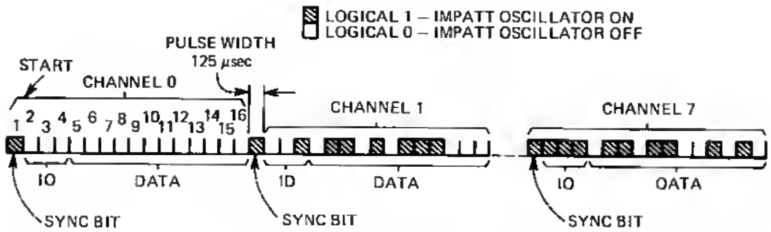

Fig. 11—Data burst timing diagram.

and offset and analog filters to prevent aliasing effects in the sampled data. Extensive use of CMOS integrated circuits reduces power consumption to a negligible level.

4.5. Transmitter-receiver

The transmitter-receiver unit includes the IMPATT oscillator, its driver-modulator, a Schottky diode receiver, a transmitting-receiving horn antenna, and associated millimeter-wave components. These include a directional coupler specially configured to fit in the restricted space available within the waveguide. The IMPATT oscillator operates at a frequency of 80 GHz and at an 8k bit per second rate.

4.6. Power supplies

The power supplies for the tractor and stabilizer have been described. The remaining supplies furnished regulated +5 volts and ±15 volts for the differential transformers and internal circuits. They are derived from nickel-cadmium batteries and have a capacity sufficient for 10 hours of operation. All supplies may be charged simultaneously without removal from the mouse. Power consumption of the mouse, excluding the tractor and stabilizer, is about 1 watt.

4.7. Miscellaneous features

The mouse assembly is over 5 meters long. A rigid assembly of this

length could not negotiate bends and would be impractical to transport and to insert into and remove from the waveguide. Each unit, therefore, is provided with universal couplings incorporating cable connectors with locking sleeves. To reduce the load on the stabilizer, all units following the torque isolator, except the gauge itself, are supported by spiders that allow the units to rotate freely about their common axis as well as to roll easily through the waveguide.

4.8. Base station

The base station has already been shown in block form in Fig. 8. It includes the base station receiver, the data decoder, and a minicomputer with peripheral equipment. Its purpose is to control the mouse and to monitor and record the received data.

The base station receiver employs conventional millimeter-wave circuitry to receive signals from the mouse and to transmit control signals to it. A received signal margin of 12 dB was obtained in measurements of the 14-km field test installation. As the waveguide loss at 80 GHz is about 0.5 dB/km or 7 dB for the entire installation, the loss margin implies that the receiver range is 38 km. Only minor improvements would be necessary to achieve adequate sensitivity for the expected repeater spacing of 50–60 km.

The data decoder has two basic functions: to convert the serially encoded data bursts into parallel format for the computer and to control the mouse. The mouse responds to seven commands; namely, start, stop, forward, reverse, power up, power down, and status. The commands are generated by pulsing an IMPATT oscillator at one of seven discrete frequencies between 25 and 68 kHz. The command signals are detected by the mouse receiver and used to operate bistable latching relays. The power down command turns off all circuits within the mouse except for the command receiver. The latter draws only 2 ma from a 0.45 ampere-hour battery so that the mouse may be left for extended periods in the power-down mode.

Meter displays indicate the distance travelled and velocity of the mouse.

4.9. Computer

The measurements are always made under computer control, although the computer may be overridden at will. The software selects the direction of motion of the mouse, the beginning and end points for the run, and performs certain housekeeping functions. As an example, the mouse is stopped when the data disk is filled. Malfunctions, such as failure of the mouse to respond to a command or lack of data from the mouse, are also indicated. Plots of the various data signals for any selected part of

the run may be obtained, but detailed analysis must be performed on a large computer.

V. CONCLUSIONS

The most convincing argument for the use of mechanical measurements in millimeter waveguide system development is provided by the *electrical* measurements of the completed installation. From these loss measurements[2] it is apparent that the mode conversion loss below 60 GHz is less than 0.05 dB/km.

This low level of mode conversion is primarily a result of process development and quality control[6] based on the use of mechanical measurements. Naturally this use depends on the ability to predict electrical losses from mechanical measurements. It is noteworthy that the theory of second order TM_{21} loss[7] was discovered largely as a result of discrepancies between the measured and predicted losses.

VI. ACKNOWLEDGMENTS

The development of the mice was a joint, intense effort on the part of many individuals. Among the many who deserve to be singled out are: T. J. West who conceived the idea of the propeller and supervised the design of several of the mice; E. Vignali, who designed the millimeter-wave sections of the long-distance mouse and the base station; E. Bochner, who wrote the software for the base station computer; K. R. Jones, who designed the external sheath mouse; E. Schultz, who contributed programs and control circuits for the rotating-head mouse; D. Olasin and D. R. Rutledge, who collaborated on the design of the internal sheath mouse; and L. W. Hinderks, who contributed greatly to the logic and software designs of several mice.

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